New Targets of Potential Mining Interest Using Gravimetric and Satellite Data: Case Study of Hercynian Rehamna Massif, Morocco

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Abstract

The known mineralization in the Rehamna Massif is essentially vein type and linked to the presence of granitic bodies and pneumatolytic - hydrothermal fluid circulations. This part of western Moroccan Meseta, belongs to the Hercynian belt, was the seat of enormous mining productions mainly base metals during the 20th century. Subsequently, exploitations are ended with artisanal extractions, in relation to exploration decline. The present work aims to search for new favourable mining targets, using gravimetric and remote sensing data. Gravimetric data allowed us to delineate leucogranitic apexes of shallow depth. Data filtering and processing consist of separation between Regional and Residual fields from Bouguer anomaly, then, calculation of horizontal, vertical and tilt derivatives to get different gravity anomalies. A Satellite image is used to obtain structural lineaments of the study region through directional filters (N0°, N45°, N90°, N135°). These treatments, supported by field investigations, enabled us to discriminate potential areas, suitable for tactical mining exploration.

Keywords: Rehamna Massif; Gravimetric data; Satellite image; Mining Hercynian

1. Introduction

The Rehamna Massif is made of Paleozoic terrains resting on a Precambrian base and covered by discordant Meso-Cenozoic sediments. Structured by a polyphase Hercynian deformation, this Massif is intruded by different acidic and basic magmatic bodies. These conditions make this area favourable for the development of mineralization, therefore, mining research.

Geophysics methods are among forceful indirect investigation techniques. They are of improvement contribution to different earth sciences disciplines, among this mining prospecting. Physical characteristics of researched target require adequate exploration process. Many studies demonstrate that discovered mineralization in the Rehamna Massif is depending on late orogenic leucogranitic bodies (Jenny 1974; Marconnet et al., 1987; El Mahi et al., 2000). Ore deposit exploited is commonly vein - type; hence the usefulness of detecting fractured zones. The purpose of our investigation is to study the relationship between mineral occurrences and geophysical signature of known and presumed granitic bodies using gravimetric data, and determining geological lineaments of the study region via satellite image filtering, to highlight potentially mineralized areas.

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2. Geology of the Study Area

The Western Moroccan Meseta is a segment of Moroccan Variscan belt, on the north of West African Craton, containing massifs of Paleozoic age. The Rehamna Massif, belonging to this area, is located between the Jebilet Massif in the south and the Moroccan Central Massif to the north (Fig.1). It is made up of Paleozoic age terrains, eroded and peneplanated, structured by the Variscan orogeny and based on Paleoproterozoic (Cocherie, 2001; Beaudin et al., 2003, Perira et al., 2015) and Neoproterozoic basement (Corsini, 1988;). These lands are covered at the borders of this Massif by tabular formations of the Meso-Cenozoic.

**Fig.1.** Situation of Rehamna Massif in Moroccan mesetian domain (Northern Provinces of Morocco, extracted from the geological map 1000000°)

The Rehamna Massif s.str, subject of our study, is subdivided into three structural zones (Fig 2):

- **The Western Rehamna** which are part of the Coastal Block, present Cambro-Ordovician terrains (Michard, 1982, El Mahi et al., 2000) modestly deformed (Guezou and Michard, 1976). This zone is bounded to the east by the NNE-SSW Median Fault (Piqué et al., 1982). The deformation gradient increases from west to east, and it’s accompanied by anchi to epizonal metamorphism (El Mahi et al., 2000).

- **The Eastern Rehamna**, bounded to the west by the Oulad Zednes Fault. It consists essentially of Lalla Tittaf and Ouled Hassine lower metamorphic Units. The age of the first one is controversial; it is attributed to the Viséen-Namurian by facies analogy with the Sarhlef Shale Formation of Central Jebilet (Huvelin, 1977; Michard, 1982). However, Baudin et al. 2003, suggest a Paleoproterozoic age after dating a metagabbro at 2136 ± 17 Ma by U / Pb on zircons (Cocherie, 2001). According to Michard et al. (2010), this dating corresponds to zircons from the underlying Precambrian crust. Whereas, Devonian age is proposed for Oulad Hassine metapelit unit (Michard, 1982, Wernert et al., 2016). This part of Rehamna is the site of most leucogranitic apexes and old mines.

- **The Central Rehamna** is located between the two previous areas. This domain includes Devonian quartzites, (locally called “Skhour”) and metaconglomerates (Piquè, 1972), Cambrian micashistes and terminal Proterozoic orthogneises of Sidi Ali dome (Corsini, 1988; Cocherie 2001, Baudin 2003; Perira, 2015). The deformation is more intense, the metamorphism reaches the mesozonal stage (Hoepffner, 1974; Diot, 1989; El Mahi, 1991).
Fig. 2. Simplified geological map of the Rehamna Massif s.str (adapted from Gigout, 1951; Baudin et al., 2002 in El Mimouni et al., 2020).

3. Granitic Outcrops and Ore Deposits

In the Rehamna Massif, two granite lineages stand out:

- Alkaline granites (Lagarde, 1989; Diot, 1989) which are represented by two batholiths: i) The Sebt Brikiyine batholith (Michard, 1967; Corsini, 1989; Hoepffner, 1974; El Attari, 2001), earlier called Si Mohamed Jerari granite (Gigout, 1951; Piqué, 1972). It is the largest batholith in the Rehamna area, located between the Lakhder and the Oulad Zednes Faults, and abuts the Median Fault (Gigout, 1951; Michard, 1967; Sirna, 1986; Diot, 1989). ii) Moulay Karkour granite, outcropping in small points to the SE of Benguerir, though, geophysic reveal a similar extension to that of Sebt Brikiyine granite (Van Den Bosch, 1981; Lagarde, 1989).

- Leucogranitic apexes, less extensive than the alkaline batholithic bodies, including Ras El Abiod, Koudiat Er Rmel, Oulad Sidi Bahilil and Bir El Gourda (Baudin et al., 2003; kholaique, 2017). The extension of contact metamorphic aureoles around the leucogranitic apexes has led many authors to presume the presence of a large batholith at shallow depth, under the Oulad Hassine plain (Hoepffner, 1974; Marconnet et al., 1987; El Mahi, 1991).

- At the mining plan, the Rehamna massif belongs to Hercynian metallogenic cycle. It was subject, in last decades, of several mining activities. Oulad Hassine, Raichet, Oulad salah and Koudiat el Bandira are the most examples of this activity, mining Sn, W, Be, Cu and Mo (Chauris & Huvelin, 1964). This mineralization depends fundamentally to known and presumed leucogranitic apexes of Eastern Rehamna (Jenny, 1974). Nevertheless, until now, all mines of this district are abandoned.
- The outcropping of leucogranitic apexes is responsible for fracturing the surrounding terrains. Residual hydrothermal fluids of magmatic differentiation process, occasionally carrying mineralization and fill fractures. Leucogranites prospecting is a research metallotect of tin and tungsten (Marconnet et al., 1987).

The following table gives an inventory of the Rehamna massif mineralization:

### Table 1. Geological setting of the mineralized area in the Rehamna Massif

<table>
<thead>
<tr>
<th>Location</th>
<th>Mineral index</th>
<th>Geological setting</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Koudiat er Rmel granite</td>
<td>Be</td>
<td>Contact metamorphism and hydrothermalism, pneumatolitic alteration and greisen</td>
<td>Marconnet et al., 1987</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Be dessimined on quartz or granite</td>
<td>Baudin et al., 2003</td>
</tr>
<tr>
<td>Ras el Abiod granite</td>
<td>Be</td>
<td>Prisms of Be in small lenses of pegmatites in the leucogenitic vein</td>
<td>Chauris and Huvelin, 1964,</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Contact metamorphism</td>
<td>El Mahi, 2000</td>
</tr>
<tr>
<td>Bir El Gourda granite</td>
<td></td>
<td>Contact metamorphism, presence of greisen veins, aplite and quartz</td>
<td>El Mahi, 1991</td>
</tr>
<tr>
<td>Oulad Sidi Bahilil granite</td>
<td>Be</td>
<td>Contact metamorphism</td>
<td>El Mahi, 2000</td>
</tr>
<tr>
<td>El Braila granite</td>
<td></td>
<td>Contact metamorphism</td>
<td>Hoepffner, 1974</td>
</tr>
<tr>
<td>Oulad Hassine mine</td>
<td>Pb-Zn</td>
<td>Mineralization vein type</td>
<td>Baudin et al., 2003,</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Contact metamorphism and metasomatose</td>
<td>Hoepffner, 1974</td>
</tr>
<tr>
<td>El Raichet mine</td>
<td>W</td>
<td>Contact metamorphism and hydrothermalism</td>
<td>Hoepffner, 1974</td>
</tr>
<tr>
<td>Oulad Salah mine</td>
<td>Ba-Pb</td>
<td>Mineralization vein type</td>
<td>Baudin et al., 2003</td>
</tr>
<tr>
<td>Koudiat El Bandira mine</td>
<td>W, Be</td>
<td>Absence of Contact metamorphism</td>
<td>Baudin et al., 2003</td>
</tr>
<tr>
<td>Leham El Bagar</td>
<td>Pb-Zn</td>
<td>Absence of Contact metamorphism</td>
<td>Baudin et al., 2003</td>
</tr>
<tr>
<td>Est of Oulad Hassine mine</td>
<td>Pb-Zn-Ag</td>
<td>Contact metamorphism and metasomatose</td>
<td>Baudin et al., 2003,</td>
</tr>
<tr>
<td>Jorf El Kahal (ou Ras El Kahal)</td>
<td>Be</td>
<td>Contact metamorphism and hydrothermalism</td>
<td>Hoepffner, 1974</td>
</tr>
<tr>
<td>Sidi Ali</td>
<td>Cu, Ba</td>
<td>Chalcopyrite associated with magmatic veins in the leucogenitic vein</td>
<td>El Mimouni et al., 2020</td>
</tr>
</tbody>
</table>

### 4. Data and Methods

#### 4.1. WGM Data

To implement our study, Bouger gravity anomaly of World Gravity Map (WGM), release 1.0 (2012) has been used, deliverable by the BGI (Bureau Gravimétrique International) (Bonvalot et al., 2012). It’s derived from Earth Geopotential Model (EGM2008) (Pavlis et al., 2008) and ETOPO1 Global Relief Model (Amante et al., 2009). This grid is provided with 1’x1’ resolution. Bouguer anomaly map has been developed based on a crustal density of 2.67g/cm3. Mining prospecting and structural geological studies are among of several applications using WGM data. Following WGM map preparation, Bouger Anomaly (BA) was gridded with minimum curvature algorithm (Fig.3). We used BA support to achieve various treatments, in order to get structures anomalies of studied area. The BA is the sum of the Regional Anomaly (RgA) and the Residual one (RsA). The RsA is obtained by removing RgA assimilated to a polynomial surface of first order. The regional field expresses deeper anomalies associated to long wavelengths, while the residual one expresses high frequencies related to shallow anomalies.
Data filtering is used extensively to isolate and enhance anomaly features of interest. The main purpose of the filters used is to highlight shallow structures. The first filter applied is the Horizontal Gradient (HG) (Cordell, 1979; Blakely & Simpson, 1986). It represents a forceful tool for mapping contacts of density contrast and shallow features (Dentith and Mudge 2014). This method is appropriate even with noised gravity data (Phillips 1998). HG is obtained by deriving residual gravity from $x$ ($\partial g/\partial x$), and from $y$ ($\partial g/\partial y$). The total horizontal gradient (THG) is calculated by using pythagora’s theorem as seen in Fig. 4 and equations 1 and 2.

\[
\left(\frac{\partial g}{\partial r}\right)^2 = \left(\frac{\partial g}{\partial x}\right)^2 + \left(\frac{\partial g}{\partial y}\right)^2
\]  

(1)

\[
\text{THG} = \frac{\partial g}{\partial r} = \left[\left(\frac{\partial g}{\partial x}\right)^2 + \left(\frac{\partial g}{\partial y}\right)^2\right]^{1/2}
\]  

(2)

Were: $g$ is the residual gravity of location $(x_i,y_i)$, and:

\[
\frac{\partial g}{\partial x} = \frac{g(x_{i+1},y_i) - g(x_{i-1},y_i)}{2\Delta x}, \quad \frac{\partial g}{\partial y} = \frac{g(x_i,y_{i+1}) - g(x_i,y_{i-1})}{2\Delta y}
\]
The second process applied to emphasise gravimetric data is the Vertical Derivative (VDR). This filter, which is defined by \(\frac{\partial g}{\partial z}\), represents the first derivative of potential gravity according to Z direction. This method enhances the shallowest geologic sources and suppresses deeper sources. Contrasting to horizontal gradient, the vertical one delineates anomalies irrespective of source orientation (Dentith and Mudge, 2014).

The third filter used is Tilt Derivative (TDR). It’s a powerful notion proposed by Miller and Singh (1994) for location of potential field sources and mining targets research (Verduzco et al., 2004). This operator is defined as the Arctan value of the ratio of the vertical potential field derivative (VDR) to its horizontal derivative (THG), as indicated in equations 3 and 4 (Miller and Singh, 1994).

\[
TDR = \tan^{-1}\left[\frac{VDR}{THG}\right]
\]  
(3)

\[
TDR = \tan^{-1}\left[\frac{\partial g}{\partial z} \sqrt{\left(\frac{\partial g}{\partial x}\right)^2 + \left(\frac{\partial g}{\partial y}\right)^2}\right]
\]  
(4)

4.2. Remote Sensing Data

Satellite data is actually a powerful tool for geological mapping and structural studies. It provide a excellent support for mineral exploration through hydrothermal alteration mapping and faults detection. To enhance geological lineaments, several manual, semi-automatic, and automatic techniques were developed (Gannouni and Gabtni, 2015; Bonetto et al., 2017, Enoh et al., 2021; Ahmadi and Pekkan, 2021).

In order to get structural lineaments of study area, band 6 of spacecraft Landsat_8 has used (ID: LC82020382016150LGN01, sensor OLI_TIRS, Path/row 202/38) acquired on 29 May 2016. Data preparation consists of extracting the interest region (Fig.5), then, a directional filter has been applied. This convolution filter is a first derivative edge enhancement (Haralick et al., 1987). It was applied in four directions (N00°, N45°, N90° and N135°), with 3*3 kernel size as given in the following matrices:

\[
\begin{array}{ccc}
-1.0000 & 0.0000 & 1.0000 \\
-1.0000 & 0.0000 & 1.0000 \\
-1.0000 & 0.0000 & 1.0000
\end{array}
\]  
N00°

\[
\begin{array}{ccc}
-1.4142 & -0.7071 & 0.0000 \\
-0.7071 & 0.0000 & 0.7071 \\
0.0000 & 0.7071 & 1.4142
\end{array}
\]  
N45°

\[
\begin{array}{ccc}
-1.0000 & -1.0000 & -1.0000 \\
0.0000 & 0.0000 & 0.0000 \\
1.0000 & 1.0000 & 1.0000
\end{array}
\]  
N90°

\[
\begin{array}{ccc}
0.0000 & -0.7071 & -1.4142 \\
0.7071 & 0.0000 & -0.7071 \\
1.4142 & 0.7071 & 0.0000
\end{array}
\]  
N135°

Fig. 5. Band 6 of Landsat image covering area of study
5. Results and Discussion

5.1. Gravimetric Data Processing

5.1.1. Regional and residual anomaly

From the $R_{gA}$ map and the $R_{sA}$ one (Fig. 6a, 6b), we notice that all anomalies are generally oriented NE-SW. This orientation is in accordance with the Hercynian structuring. The intensities of $BA$ are ranging from +70 mGal to 140 mGal, and gradually decrease from NW to SE.

![Fig.6](image-url)  
Fig.6. Maps show the Regional Anomaly (a) and Residual Anomaly (b)

$R_{sA}$ map reveal several shapes of positive and negative anomalies, ranging from -16 to +12 mGal. It shows a central negative anomaly oriented NE-SW, which includes most granites of Rehamna, surrounded by a positive anomaly. Quite possibly, negative anomaly is related to mass deficiency of the granites and leucogranitic apexes of subsurface. Positive anomaly reflect the Palaeozoic and Proterozoic basement uprising.

5.1.2. Horizontal gradient

We proceeded to a horizontal derivative filters to emphasize changes of density in the horizontal gradient according to both directions X and Y. This process gives more details and discriminate several shapes of anomalies as seen in Fig.7.

![Fig.7](image-url)  
Fig.7. Total Horizontal Gradient of residual anomaly surimposed to granitic bodies and faults. (granites of: SB: Sebt Brikiyine; RA: Ras el Abiod; SBH: Sidi Bahilil; KR: Koudiat Rmel).
The analysis of THG map shows four main low anomalies: the first one at NW related to Doukkala basin, the second in the center includes the most of Permian leucogranites apexes, indicate the mass deficiency of the granite. The third anomaly in the Southwest of Bengurir could indicate Moulay Karkour granite, the fourth at the SE designate Cretaceous and Eocene formations of phosphates. High anomalies express perhaps the uprisin of basement. We notice also a tendency of forms to be E-W, mainly in Eastern Rehamna.

5.1.3. Vertical derivative (VDR)

VDR is used to better discriminate the anomalies of high frequencies. From the analysis of the VDR (Fig. 8), we distinguish several shapes of anomalies with differences amplitude and direction. Two types of negative anomalies stand out:

- A global negative anomaly that begins with the SB Granite, and continues eastward to subdivided into two branches towards the Oulad Zednes shear zone: the first branch continues eastward; beyond RA granite, and the second extends northward (Kef el Mouneb and Dar Khalifa Brik). This anomaly brings together the Granite of SB and the leucogranites of RA, SBH and BG which indicates that these granitic bodies could have a genetic relationship. The Koudiat Rmel granite escapes this distinction.

- The negative anomaly related to the RA Granite continues eastward beyond the El Bandira Mine in the Sidi Ben Azzouz region. El Bandira and Rhaichet mines are located in the borders of this anomaly.

- Restricted anomalies: case of the negative anomaly linked to the Hassine Mine which extends to the east of El Menaat near of Guelb Boualla. This anomaly is most likely related to presence of a leucogranitic apex. This result confirms the hypothesis of Marconnet et al., 1987. Two other negative anomalies, the first one located in SE of Skhour Rehamna, extending between Jorf el Beïda and Cherfa. A Pb index is bordering west of this anomaly. The second anomaly at Kef el Mounib area. Michard, (1968a) predict the presence of a thermal front in the South of Skhour and at Kef el

![Fig. 8. Vertical Derivative (VDR) superimposed on map of granites, faults, mineral indexes and old mines (Mines of: Has= Hassine; Sal= Oulad Saleh; Rha= Rhaichet; Ban= el Bandira)](image-url)
Mounib (Piqué, 1972), which confirms the occurrence of leucogranitic apexes in these sites of low density.

- On the other hand, positive anomalies are generally related to uprising of basement and metamorphic units.

### 5.1.4. Tilt derivative

The analysis of tilt derivative map (TDR) shows that all anomalies of first vertical derivative are generally conserved; with a better delineation of sources edges (Fig. 9). Values of TDR angle are ranging from (−π/2) to (+π/2) radians as a result of Arctan trigonometric role. It discriminate areas of known and presumed granites and basement as described above.

TDR show furthermore the relationship between SB granite and leucogranitic apexes.

### 5.2. Landsat Data Processing

The directional filters results of Landsat data are summarized in Fig. 10. From the analysis of the synthetic image (e), we can distinguish four main family directions, which explain the polyphase tectonic style of Rehamna massif: N-S to NNE-SSW at Western Rehamna, NNE-SSW to NE-SW at Central zone, NE-SW to E-W (rarely NNW-SSE) at Eastern Rehamna. Similar directions was obtained using aeromagnetic and gravimetric data (Benyas et al., 2021; Benyas et al., 2022).
Fig. 10. (a,b,c,d) directional filters applied to band 6 of Landsat 8 image, (e) interpretation of results.

Fig. 11 includes lineaments, mineral occurrences and old mines surimposed to VDR map, illustrate the relationship between these elements and anomalies of existent and presumed leucogranite apexes in the study area. As described above (negative anomalies), and the lineaments results, we can select four main targets of potential mining interest related to likely leucogranite apexes (Fig. 11).
6. Conclusions

- The interpretation of the geophysical signal, essentially vertical and tilt derivatives, combined with the distribution of mineral occurrences and geological setting, reveals the spatial distribution of leucogranitic apexes and their relationships with other granitic bodies.
- We were able to demonstrate the relationship between granite intrusions and mineralization in the Rehamna Massif; this mineralization is generally located at the edges of the existent and presumed leucogranitic apexes.
- Geological lineaments extracted from Landsat image reveals an Est to west clockwise rotation of directions. Field investigations able us to distinguish four main faults families: NNE-SSW, NE-SW, E-W and NNW-SSE, with dominance of the E-W family for magmatic and mineralized veins.
- The sites selected as targets of potential mining interest includes presumed leucogranitic apexes detected via gravimetric data filtering, and lineaments extracted from Landsat image.

These results can guide a tactic mining exploration essentially for pneumatolytic and hydrothermal deposits, and enhance the Rehamna area from a mining perspective in relationship with the economic development of this region. The present study reveals the advantage of using spatial open-source data previously in mining exploration, an asset in any strategic phase of a mining project: reduction in costs and time.

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References


